

Evaporation, Seepage and Water Quality Management in Storage Dams: A Review of Research Methods

Ian Craig¹, Vasantha Aravinthan¹, Craig Baillie¹, Alan Beswick⁴, Geoff Barnes¹, Ron Bradbury², Luke Connell³, Paul Coop², Christopher Fellows², Li Fitzmaurice⁴, Joe Foley¹, Nigel Hancock¹, David Lamb², Pippa Morrison¹, Rabi Misra¹, Ruth Mossad¹, Pam Pittaway¹, Emma Prime³, Steve Rees¹, Erik Schmidt¹, David Solomon³, Troy Symes¹ and David Turnbull¹

¹*Cooperative Research Centre for Irrigation Futures, National Centre for Engineering in Agriculture, Australian Centre for Sustainable Catchments, University of Southern Queensland,*

²*School of Science and Technology, University of New England,*

³*Department of Chemical and Biomolecular Engineering, University of Melbourne &*

⁴*Queensland Department of Natural Resources and Water*

One of the most significant sources of water wastage in Australia is loss from small storage dams, either by seepage or evaporation. Over much of Australia, evaporative demand routinely exceeds precipitation. This paper outlines first, methodologies and measurement techniques to quantify the rate of evaporative loss from fresh water storages. These encompass high-accuracy water balance monitoring; determination of the validity of alternative estimation equations, in particular the FAO56 Penman-Monteith ETo methodology; and the commencement of CFD modeling to determine a 'dam factor' in relation to practical atmospheric measurement techniques. Second, because the application of chemical monolayers is the only feasible alternative to the high cost of physically covering the storages to retard evaporation, the use of cetyl alcohol-based monolayers is reviewed, and preliminary research on their degradation by photolytic action, by wind break-up and by microbial degradation reported. Similarly, preliminary research on monolayer visualisation techniques for field application is reported; and potential enhancement of monolayers by other chemicals and attendant water quality issues are considered.

Key words: *Evaporation Control; Seepage; Penman-Monteith Equation; Monolayer*

The current concern over global climate change is bringing water sustainability in Australia into sharp focus. Increasing temperatures and decreasing rainfall are presenting very real threats to profitable agricultural production. Irrigated agriculture consumes approximately 70% of fresh water consumed, but this resource is declining. In Australia, approximately one million small dams account for 7000 GL or 9% of the total water stored. In the worst case scenario where a dam has water in it all the time, up to 40%

of the water might be lost due to evaporation, based upon a typical evaporation figure of 2m per year and a dam typically filled to a depth of 5m.

Unfortunately, precise information is scarce on dam and channel numbers, size, depth and water retention times. A detailed GIS/computational based study is required to determine this accurately, but until this is performed, a rough estimate is that well over 1000GL/yr of water stored for agricultural purposes might be lost to evaporation. This

Figure 1: Illustration of the QNRW-commissioned evaporation control evaluation program



Source: Details can be accessed at www.ncea.org/evaporation resources

certainly represents a gross inefficiency in terms of the environmental sustainability of our fresh water resource.

A further important consideration is the difficulty of maintaining water quality standards in small storages which often receive nutrients from runoff. Reducing evaporation and improving water quality through effective management techniques has the potential to significantly improve agricultural water use efficiency in Australia. This paper outlines the research recently commenced by a multidisciplinary team under the auspices of the Cooperative Research Centre for Irrigation Futures (CRC-IF) to address this general issue, and in particular techniques for the minimisation of evaporative losses.

Background

During 2002-2005 the National Centre for Engineering in Agriculture (NCEA) at the University of Southern Queensland (USQ) evaluated the performance of various different types of commercially-available dam cover, as illustrated in Figure 1. Principal outcomes from this investigation, commissioned by the Queensland Department of Natural Resources and Water (QNRW) comprised:

- important new knowledge regarding the field performance of various different types of cover;

- technology required to accurately assess evaporation and seepage losses; and
- increased public awareness of the potential for evaporation reduction on water storages.

The study revealed evaporation was reduced by approximately 75% for shade cloth covered dams, up to 95% with dams covered with a properly functioning floating cover, and approximately 5 to 30% with dams covered with a cetyl alcohol-based chemical monolayer (Craig et al. 2005). Shade cloth covers used primarily for algal control, have cut evaporation from Victorian water storages by 90% (CSIRO).

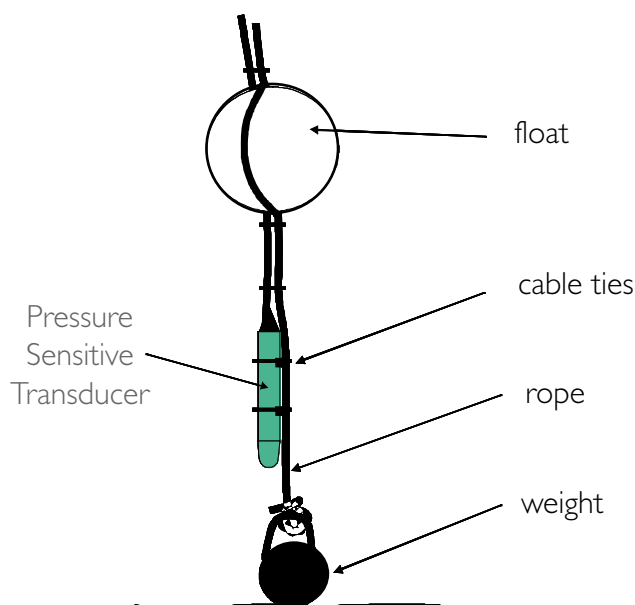
The study concluded that high evaporation savings are possible if physical covers are used on small farm dams less than 10ha in size. Physical covers can also be used on larger dams, but they are generally uneconomic due to the high capital investment required and despite the very good evaporation protection provided. And clearly, increased cost of water might justify the physical cover of the larger dams.

In contrast, economic analyses indicate that for larger dams chemical monolayers represent potentially the best option for protection of agricultural water in Australia, even though they currently provide significantly poorer protection. However, the dam covers evaluation study indicated clear deficiencies in current monolayer products and techniques, and also the potential for significant improvement. Our recently commenced monolayer research is outlined in this paper.

Dam Evaporation/Seepage Monitoring

The QNRW project (introduced above) necessitated the development of a novel experimental method to measure and record water depth, and hence dam water volume. An accuracy of $\pm 1\text{mm}$ was achieved using submersible Pressure Sensitive Transducers

Figure 2: The PST water depth sensor suspension mechanism (schematic)



(PSTs) with custom (per unit) compensation for water temperature variation. Each PST unit was placed at a constant 30cm height above the dam floor by a float-weight arrangement as illustrated in Figure 3.

Logged PST data was compared to 15-minute Penman-Monteith-based estimates of evaporation derived from an adjacent weather station (AWS). This enabled evaporation to be separated from seepage losses (Craig 2006). Seepage values for Australian farm dams were found to be very variable, from almost nothing to several millimetres per hour.

The water balance of a dam or water storage over a specified time interval may be expressed as:

$$Q_{in} + P + \delta D = Q_{out} + S + E \quad (1)$$

where Q_{in} is the inflow, P is precipitation, δD is the change in level measured using a PST unit, Q_{out} is the outflow, S is seepage and E is the evaporation rate (all in mm/day).

Clearly, water volume is not strictly proportional to depth (due principally to the slope of the dam walls) but for small time- and depth- intervals the error involved in

this approximation is negligible for large dams, <1%.

To increase the accuracy of this analysis, tests on dams are usually carried out when Q_{in} , Q_{out} and P are zero. The evaporation term E can be estimated from the Bureau of Meteorology SILO database, or, as indicated above, from AWS-recorded meteorological parameters obtained at the actual dam site using the Penman-Monteith equation (Craig 2006; Jensen 2005). These techniques offer potentially more accurate estimates since cloud cover and local windspeed are actually measured at the site, but precautions have to be taken to ensure that all meteorological parameters are measured and logged accurately, particularly solar radiation.

The PST/AWS method confirmed that evaporation losses in small farm dams were typically 4-7mm/day in summer, rising to 10mm/day when air temperatures exceeded 40°C. The analysis also revealed that Australian summer night-time evaporation due to heat advection effects (Brutsaert 1982) ranged from 10 to 30% of the total daily evaporation.

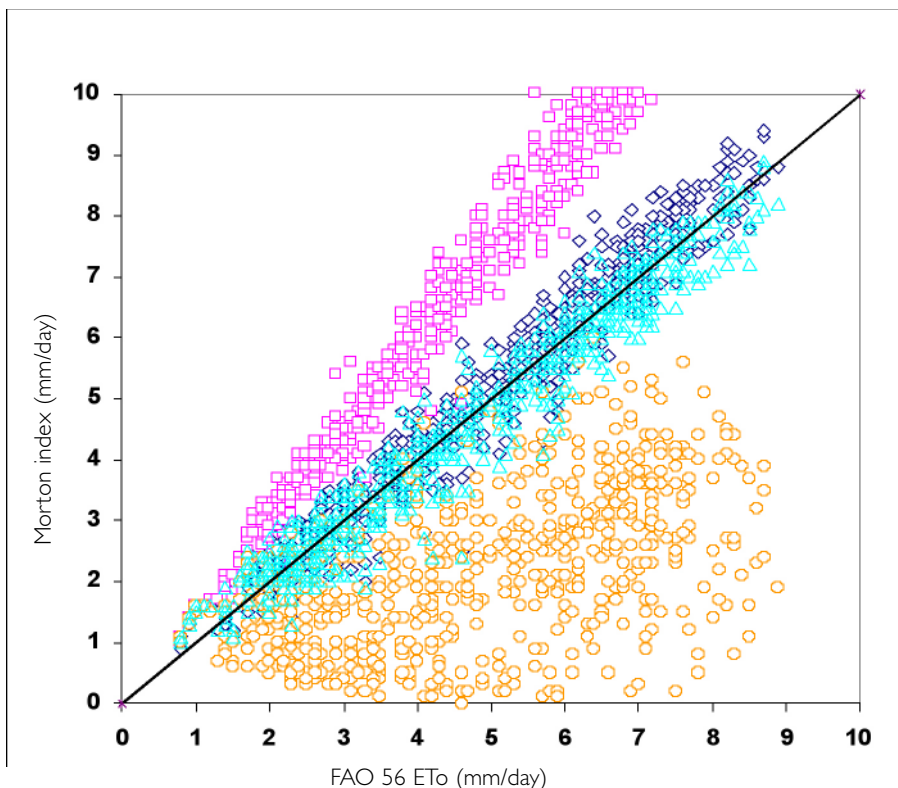
The appropriateness of using the ETo values derived via the FAO56 formulation of the Penman-Monteith equation (Allen et al. 1998) as indicative of open water evaporation is often regarded as open to question because further simplifications are possible (Valiantzas 2006). However, Figure 3 shows a comparison of daily data from the SILO database (patched point datasets available at <http://www.nrw.qld.gov.au/silo/>) for the St George region, South Queensland, from the 1 January 2005 to the 26 November 2006, in which four alternative evaporation equations offered by Morton (1983) are plotted against daily FAO56 ETo. These are:

1. Morton Potential Evaporation (point source evaporation in dry environment);
2. Morton Lake Evaporation (open water evaporation from a large reservoir);
3. Morton Wet Environment (representing a recently irrigated field); and
4. Morton Actual Evaporation (limited according to water availability).

Figure 3 shows that both 2 and 3 above are in close agreement with the estimates derived via FAO56, such that the FAO56 ETo equation suggesting that its use is acceptable for the estimation of open water evaporation. (Further analyses are provided in Morrison & Craig 2007.)

A rough estimate for the seepage loss at a particular dam site is then simply the difference

Figure 3: Comparison of point potential evaporation (square), Morton's Lake evaporation (diamond), Morton's Wet Environment evaporation (triangle) and Morton's Actual evaporation (circle) all plotted against the FAO56 Penman-Monteith ETo estimates



between the δD and E terms of equation (1) derived using FAO56 methodology. However, to increase the accuracy of this analysis, particularly for small dams, it needs to be assumed that

$$E_{\text{dam}} = K_{\text{dam}} \times E \quad (2)$$

where K_{dam} is a dam factor which relates evaporation of the dam to the FAO56 Penman-Monteith estimate. This approach is worth pursuing because factors similar to K_{dam} have been shown to be successful for large irrigation water reservoirs using pan evaporation as substitute for FAO56 E_{To} (Martinez-Alvarez et al. 2007).

Dam Evaporation Modelling

Clearly, the value of K_{dam} introduced in equation (2) is likely to be a complex function of general dam morphometry. This may be expected to modify the surface air flow and in turn heat exchange, water vapour exchange and in-dam water circulation.

With the eventual objective of understanding and evaluating k_{dam} , an analysis of the mass and energy flows over a

typical small day has been commenced using computational fluid dynamics (CFD) and dubbed 'DamCFD'. Preliminary results are set out in Craig, Mossad and Hancock (2006).

Using a 2-D approximation, a computational grid of the vertical section of a 100m x 100m x 5m ring tank (Figure 4) was established using GAMBIT software and CFD calculations were performed using FLUENT version 6.2. Once boundary conditions are established, the software performs a finite-volume-based numerical technique to solve the governing equations which are Navier-Stokes equations (second order, non-linear partial differential equations) and the energy equation to determine the flow field, flow velocity and temperature distribution within the grid.

Due to the extreme (and unavoidable) complexity of the model, a transient solution was attempted with small time steps in order to achieve computational stability. This was successful and an example of the solution, at around 800 seconds from commencement, is presented in Figure 5.

Figure 4: Dimensions of the ring tank modeled

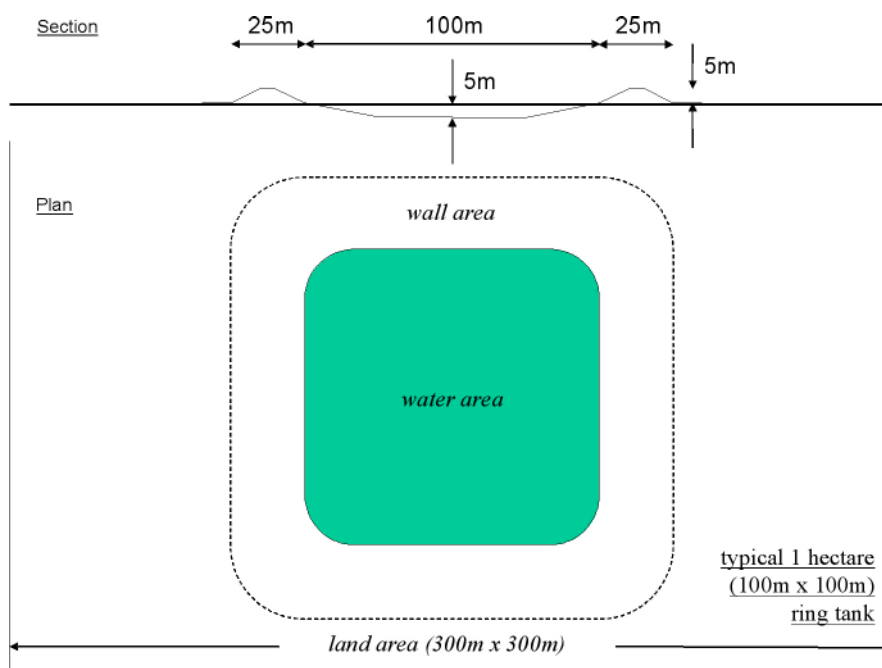
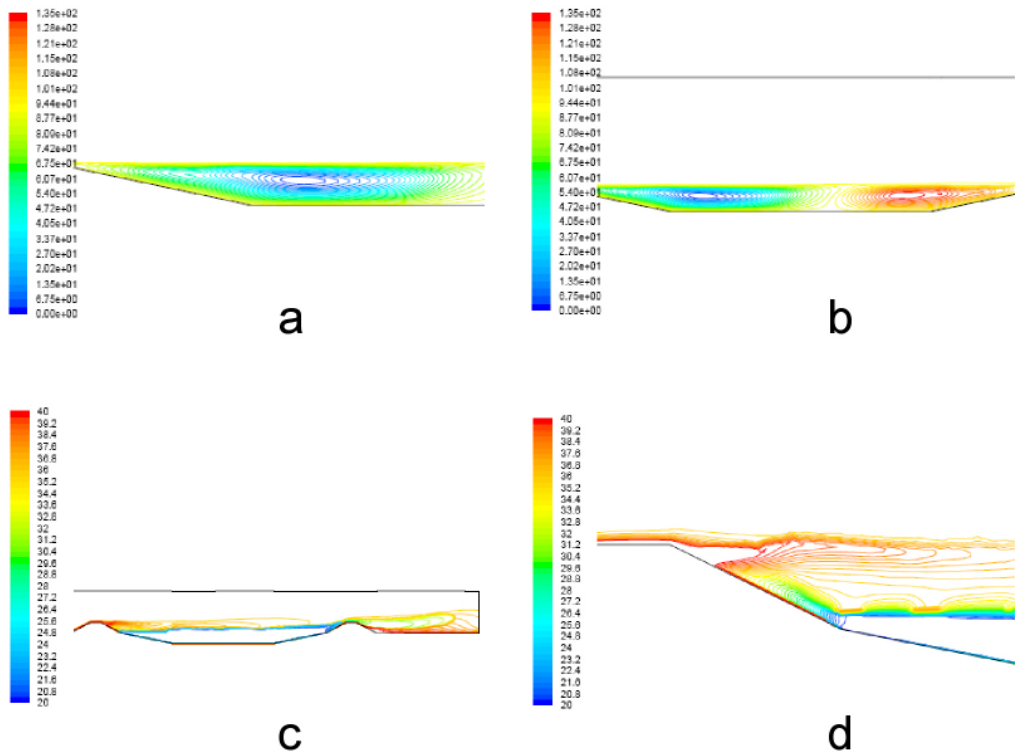


Figure 5: Contours of the flow field (streamlines) and temperature obtained by CFD modelling of dam evaporation using the model of Figure 4. a: close up of the streamlines of the flow at upstream of the ring tank; b: streamlines of the flow in the ring tank; c: temperature contours; and d: close up of temperature contours upstream of the ring tank.



As indicated above, data eventually generated by DamCFD for a variety of weather conditions and dam morphometries will hopefully provide the basis for a simple dam factor-based algorithm to relate farm dam evaporation to simple indices such as the P-M formula. The model will be validated using remote sensing, laser or eddy correlation techniques. These will be used to obtain real time non-equilibrium measurements of evaporative flux within the dry to wet boundary transition region and across the dam as a whole, and may be compared with transition algorithms for small ponds suggested by Morton (1983) and Sartori (2000).

Monolayer Research

As noted above, monolayers offer a potentially attractive prospect of an economical cover

to reduce evaporation for large agricultural dams (Barnes 1993). Monolayers comprise amphiphilic molecules - long single chain molecules with one hydrophilic and one hydrophobic end. This structure enables the molecules to sit at the water surface and pack closely together forming a film that is only one molecule thick (approximately 2nm). It is the close packing of these molecules that provides the resistance to water evaporation.

Traditionally, the monolayer materials have been the higher alcohols, that is, linear hydrocarbon chains with 16 or 18 carbons and with an alcohol (-OH) group at one end (hexadecanol or cetyl alcohol and octadecanol or stearyl alcohol respectively). The longer the carbon chain, the more effective the monolayer is at retarding water loss, but at the same time a longer chain decreases the affinity of the monolayer

Figure 6: Water\$avr™ (cetyl alcohol) monolayer seen spreading across the surface of a dam (courtesy of Nylex Water Solutions). Visual observation of monolayers in this way is only possible under conditions of light wind



for water, retarding the rate at which the monolayer will spread on a water surface, and increasing the brittleness of the monolayer. C16-18 alcohols have been selected in the past because they offer high resistance to water evaporation and small flakes of the solid alcohol spread spontaneously to form monolayers with a high molecular packing density. Savings of up to 50% of the water lost by evaporation have been reported in some field trials (La Mer 1962).

Monolayers of cetyl alcohol (a mixture of C_{16} and C_{18} alcohols) are biodegradable and have been cleared for use on drinking water storages by national regulatory agencies. They have a minimal effect on the transport of oxygen through the air/water interface, hence a minimal impact on aquatic biota, but can significantly retard the loss of water by evaporation (Figure 6).

However, monolayers of long chain alcohols suffer from several problems that have restricted their use. Their spreading rate is too slow, and they are lost by evaporation, bacterial action, and wind so that their useful lifetime on a water surface is rarely more than two days. Thus, although the material cost is low, there are significant costs in monitoring and reapplying the monolayer. Optimising the performance of monolayers, including a full investigation of degradation mechanisms, and also improved application

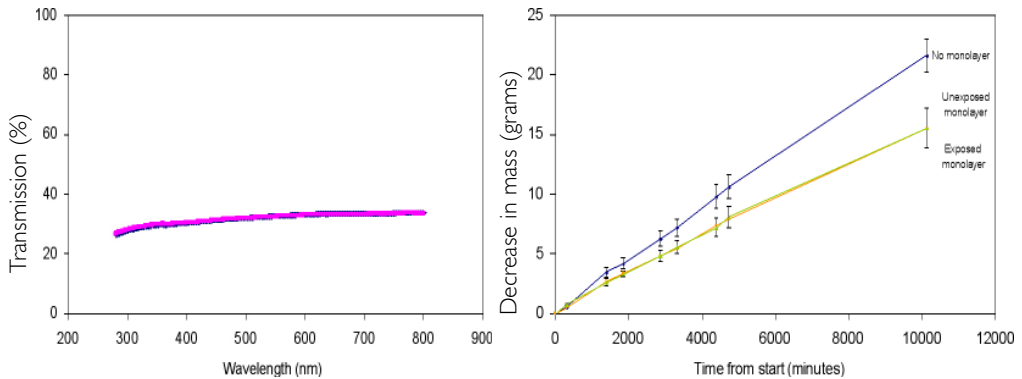
methods, is currently the focus of CRC-IF funded research efforts at USQ and UNE. Collaboration with the CRC for Polymers is focusing on synthesising new potential monolayer compounds at the University of Melbourne (UoM).

Photolytic degradation

Ultraviolet radiation (UV) incident on the earth's surface ranges from 295 to 400 nm. Wavelengths below approximately 295 nm are completely attenuated by the earth's atmosphere. UV plays an integral role in the photodegradation of different types of materials from polymers to human skin. Therefore, an important question in this research is whether or not UV radiation is a factor in monolayer degradation. To resolve this question, two tests were performed. The first test looked at the variation in optical transmission characteristics of the monolayer before and after exposure to UV radiation. The second test looked at the variation in water evaporation rates when using exposed and unexposed monolayer.

Transmission characteristics were tested by casting thin films of hexadecanol and octadecanol on one side of quartz cuvettes (quartz transmits the majority of incident UV radiation) and exposing the materials to approximately 5.3 MJ/m² UV radiation (this exposure is equivalent to two and a

Figure 7: Optical transmission characteristics of octadecanol before and after UV exposure (a) and evaporation rate of water with exposed/unexposed monolayer compared to water without monolayer (b)



half full days of solar UV exposure during mid summer). Transmission qualities of the monolayer materials were then tested at 30 minute intervals throughout the exposure period. Maximum variation in the transmission qualities of the materials over the course of the UV exposure period was in the order $1.4 \pm 0.4\%$ (Figure 7a). This can be considered as negligible as it is within the $\pm 5\%$ error margin of the instruments.

Evaporation rates of water with exposed and unexposed monolayer were also tested. Containers of distilled water with cetyl alcohol monolayer were exposed to approximately 5.3 MJ/m^2 of UV radiation and compared to containers of distilled water with unexposed monolayer. Results showed that there was negligible difference in the rate of evaporation of the water (Figure 7b).

Breakup via wind - windtunnel research

A windtunnel has been constructed at USQ to examine the spreading performance of different chemical monolayer prototype formulations produced by CRC-Polymers in terms of their spread and resistance to breakup, as well as microbial and UV degradation. A significant factor that affects the performance of a monolayer is the wind. Current research is looking at

Figure 8: Wind tunnel test showing the area of water covered with cetyl alcohol monolayer (depicted by white specs) being pushed back by air travelling across the tray in a left to right direction. The leading edge of the monolayer is clearly visible



how wind speed affects the spreading and performance of the cetyl alcohol monolayer in a controlled environment. The wind tests are being conducted in a specially designed wind tunnel that gives uninterrupted visual access to the tests being carried out. This is possible through the use of clear acrylic sheets on the top and sides of the working section of the wind tunnel. Results show that the monolayer and the leading edge of the monolayer can be visualised by the addition of very fine particles to the monolayer surface (Figure 8). Wind tunnel tests are still ongoing.

Degradation by microbes and organic microlayers

The efficacy of an artificial monolayer in reducing evaporative water loss will depend partly on the resilience of the compound to microbial degradation. Laboratory studies confirm that the common freshwater bacteria *Pseudomonas* and *Flavobacterium* sp are capable of utilising hexadecanol as a carbon source (Chang, McClanahan & Kabler 1962). Phototrophic bacteria are also highly likely to utilise monolayer compounds such as hexadecanol. The esterifying alcohols farnesol, hexadecanol, hexadecenol, tetradecanol, phytol and octadecanol are all naturally synthesised components of bacteriochlorophyll (Glaeser & Overmann 2003). Wax esters are commonly used by procaryotes as substrates for carbon/energy storage compounds (poly-(-hydroxyalkanoate compounds Madigan, Martinko & Parker 2003). Biochemical studies indicate that the common freshwater bacterial species *Acinetobacter* can also utilise a broad range of various chain-length saturated and unsaturated fatty alcohols ranging from C_{12} to C_{20} as substrates. Polluted streams favour the population growth of *Acinetobacter* to the extent that it is used as an indicator species for ecological monitoring (Lemke et al. 1997).

Naturally-derived surface films (microlayers) occur on most water bodies (Norkrans 1980). The earliest evidence for the existence of microlayers was inferred from observations on the movement of dust particles on the surface as affected by water currents (Goldacre 1940). Early quantitative studies indicated that natural films on water bodies such as lakes and ponds may induce surface pressures exceeding 30 dynes cm^{-1} . Later studies indicated that the thickness of these natural films may reach 500 μm (Munster, Heikkinen & Knulst 1998). Lipids are the major constituents of microlayers, with saturated and unsaturated fatty alcohols and acids with a carbon chain length of C_{12} to C_{22} the most common. The precursors

of microlayers on lakes and dams are the humified degradation products of plant cuticular waxes. The activity of bacteria and other aquatic microbes is concentrated within these microlayers, at levels from 8 to 280 times greater than in the bulk subsurface water.

Therefore, microlayers have the potential to adversely affect the performance of artificial monolayers in retarding evaporative loss on water storages in two ways. The first is via the enhancement of bacterial populations capable of degrading long-chain compounds such as cetyl and stearyl alcohols. The second is via the naturally occurring amphiphiles within microlayers acting as impurities within the monolayer, lowering the evaporative resistance of the surface film (Barnes & La Mer 1962). A key feature of the project will be to screen candidate monolayer compounds for their microbial resilience, and to investigate how water quality and the presence of pre-existing microlayers affects the evaporative resistance of artificial monolayers applied to a water storage.

Potential for monolayer enhancement

Monolayers based on cetyl or stearyl alcohol are permeable to oxygen and need only be present in a layer one molecule thick; enabling large surface areas to be covered with minimal environmental disturbance. Some preliminary investigations have indicated that the performance of cetyl alcohol based monolayers may be significantly enhanced with the addition of other chemicals. For example, poly (vinyl stearate) (PVS) a polymer with a comb-like structure which may enhance the resistance of the monolayer to stress. Selection of food-grade compounds, or compounds chemically similar to naturally occurring plant waxes will minimise any adverse environmental impacts associated with the application of artificial monolayers. Collaboration with UoM, through the CRC for Polymers, is investigating the potential to overcome the afore-mentioned limitations

with the cetyl/stearyl alcohol system, such as loss of the actual monolayer by evaporation, bacterial degradation, and wind, resulting in a short useful lifetime on a water surface (2 days). The synthesis and testing of a range of novel compounds, including polymers, will allow for the properties of the monolayer to be controlled, resulting in the best balance of desired properties.

Monolayer Visualisation

In order to quantify the importance of the mechanisms responsible for monolayer degradation, and the most effective methods of spreading a monolayer over a surface, it is desirable to have a method of visualising the monolayer and monitoring its location over space and time. The presence or absence of the monolayer may be monitored with a conventional visible light camera under 'light' wind conditions where capillary waves occur in the absence but not in the presence of the monolayer (e.g. Vines 1960). However, the presence or absence of the monolayer is not the only information required: there is strong experimental evidence that a close-packed monolayer is required for retarding evaporation, and that a disordered monolayer permits a high evaporation rate (Barnes & Quickenden 1971).

The group at UNE is currently investigating a number of optical methods for quantifying the presence of monolayers on the laboratory scale and determining whether they are ordered or disordered. Current methods include observation of the ratio of plane-polarised to perpendicularly-polarised reflected light as a function of reflected angle, the near infrared reflectance spectroscopy of monolayer films (Gericke, Simon-Kutscher & Hühnerfuss 1993), laser reflection from the water surface (Jiang et al. 1992; Saylor, Szeri & Foulks 2000), and the use of a horizontal transducer to measure surface tension (Perez 1994). Current research at UNE is focused on the latter two techniques.

Laser Reflection (LR)

The LR technique (Figure 9) involves reflecting a laser beam off artificially-generated plane capillary waves. The vertical extent of the rapidly-oscillating reflected laser beam is proportional to the amplitude of the capillary waves. The presence of monolayers on the water reduces the height of waves due to a damping effect. A light sensing transducer (linear integrating CCD array) can be used to monitor the angular spread of the reflection pattern. Initial results giving the dependence of the angular spread of the reflection pattern

Figure 9: The Laser Reflection technique, (a) without and (b) with monolayer coating

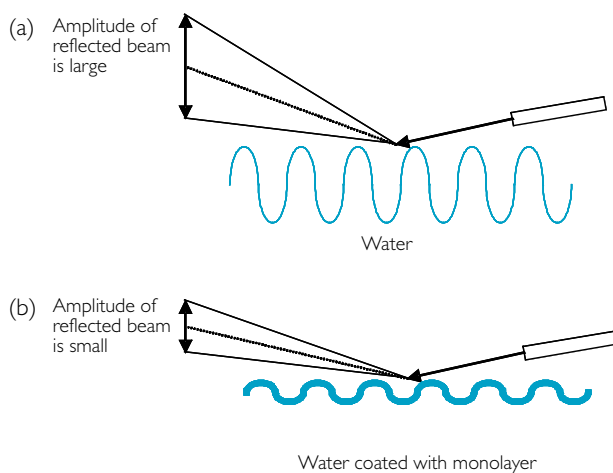
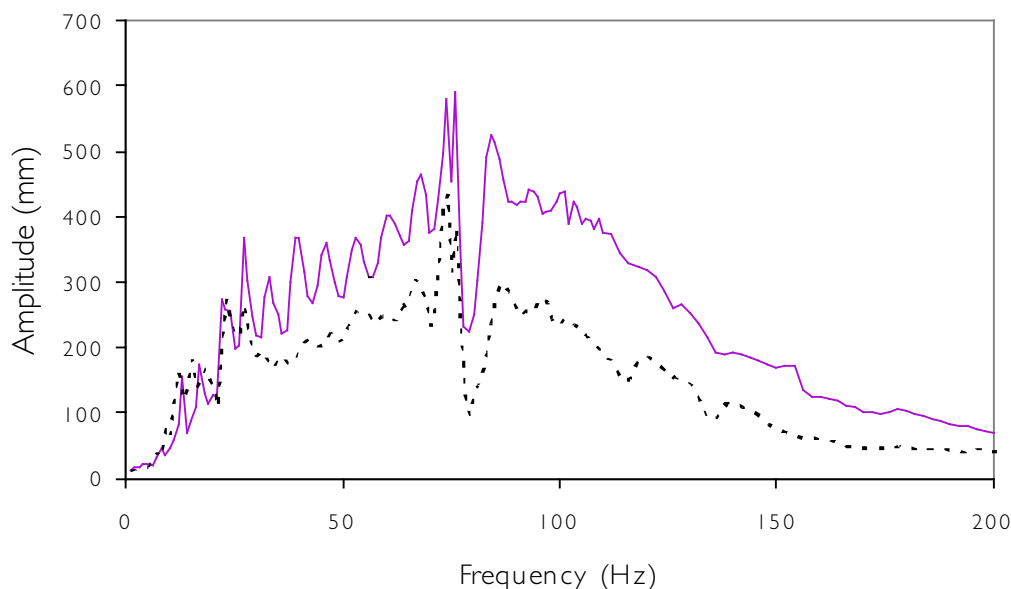


Figure 10: LR results with laser oriented 74 degrees from vertical. Solid line is without monolayer coating, broken line is response with a hexadecanol monolayer



on the frequency of the capillary waves in the presence and absence of monolayer are shown in Figure 10.

Horizontal Transducer (HT)

The HT technique relies on the reduction of surface tension caused by the presence of a monolayer. Surface tension can be measured using a Wilhelmy Plate which usually consists of a piece of filter paper held vertically in contact with the fluid. Any decrease in surface tension is measured by an apparent decrease in the weight of the plate. This is clearly impractical for field measurements as the mechanism would bob up and down in any kind of wind. However, there is an alternative pressure transducer that measures force in the horizontal rather than vertical direction. A sensitive ammeter and needle is used to hold a floating Teflon boat steady when there is an imbalance of monolayer one side, and reference water on the other. The ammeter is connected to a feedback circuit which is fed into the ammeter coil to keep it steady. The current can then be read and is a linear measurement of surface tension. A prototype of this HT technique

has been assembled and demonstrated to give good results on a laboratory scale, and is planned to develop robust instrumentation based on this method for field use.

Water Quality Management

Water quality management for storages where evaporation control techniques are implemented depends both on i) water quality from an ecosystem point of view, and ii) the intended commercial use of the stored water, whether for crops, animals or humans. All methods available for evaporation control are likely to have some environmental impacts, and these need to be fully researched and quantified.

Shade structures reduce the solar radiation energy available for evaporation, reduce wind velocity over the water surface and increase the humidity of air under the cover. However, as the cover is not in direct contact with the water, some airflow still takes place allowing convection mixing of the water to occur, although this may be reduced. Reduction in sunlight might alter the photosynthetic balance within a water column, but this can be put to useful effect by reducing the

growth of harmful algae within storages. This would offer an advantage for small storages which normally experience problematic algal growth in response to elevated concentrations of nitrogen and potassium. The use of shade cloth as an algal management system is currently being investigated in Victoria Australia in a CSIRO funded project (Hunter 2002).

There might be more significant environmental impacts associated with continuous floating covers because they are in direct contact with the water. With floating modules, some of the water surface area is left uncovered which might result in lesser impacts. But with continuous plastic covers, wind action over the water surface is halted, which could result in reduction of oxygen transfer that would otherwise be supplied through surface aeration and convection induced by wind currents. Plastic covers have the potential to adversely impact on natural aquatic ecosystems via changes to light penetration and oxygen diffusion. Before being recommended for use, the effects of different physical covers on water quality and aquatic ecology need to be assessed.

The full ecotoxicological implications of using chemicals for evaporation control also needs to be fully investigated. Monolayers are attractive as they are only 2nm or so thick and allow good transfer of oxygen and only have to be applied in tiny amounts. They in fact mimic the characteristics of natural monolayers and are therefore likely to have minimal environmental impact. However, the same might not be true of oil films which are hundreds of times thicker. While biodegradable oil films might offer an attractive option for agriculture, the effect on water quality due to increased bacterial activity or any other ecological impact needs to be fully investigated for each product introduced.

Conclusion

There are eight conclusions that we can draw from the research outlined above.

- Within the subtropical regions of Australia, evaporative demand routinely exceeds precipitation. Results from a project funded by Queensland Natural Resources and Water (NRW) indicated that physically covering a dam could substantially reduce evaporation. However, the cost-effectiveness and the environmental impact of this strategy must be evaluated.
- The use of chemical monolayers offers a feasible alternative (Barnes 1986), enabling larger surface areas to be covered with minimal environmental disturbance.
- The chemicals used for monolayers must be able to withstand the harsh solar radiation and wind environments of Australia. However, initial investigations have demonstrated that cetyl alcohol is not affected by high levels of ultraviolet radiation. It appears though that most surface films are affected by wind.
- The performance of chemical monolayers might also be affected by the presence of bacteria or microlayer impurities in the water.
- Some preliminary investigations have indicated that the performance of cetyl alcohol based monolayers might be significantly enhanced with the addition of other chemicals. For example, poly vinyl stearate (PVS) a polymer with a comb-like structure which might enhance the resistance of the monolayer to wind stress (Fukuda et al. 1979).
- Selection of food grade compounds, or compounds that are chemically similar to naturally occurring plant waxes will minimise any adverse

environmental impacts associated with the application of artificial monolayers. However, the potential for the derivatives of plant waxes in natural microlayers to disrupt the function of artificial monolayers must be assessed.

- Research is underway to explore other molecules with longer chain lengths which might be more resistant to microbial attack. It is known that certain hydrophobic surface films form naturally on impounded waters

such as lakes and stagnant pools (Goldacre 1949). Model systems such as the biochemistry of the animal rumen might provide insights into likely candidate molecules (e.g. Bugalho et al. 2004).

- A number of techniques show promise for assessing the degree of monolayer coverage and the nature of the monolayer (ordered or disordered) in field measurements. These include laser reflection from the water surface and the use of horizontal transducers to measure surface tension.

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Correspondence to:

Ian P. Craig

Faculty of Engineering and Surveying

University of Southern Queensland (USQ)

Toowoomba, 4350, Queensland

AUSTRALIA

Email: craigi@usq.edu.au